3D SAR Made Simple

by

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Goal of Talk

- Describe a basic Radar imaging system using simple terms – minimal equations.
- Highlight the fundamental radar image formation challenges.
- Define Synthetic Aperture Radar (SAR)
- Show how two dimensional concepts can be extended to form three dimensional images.

Radar Defined

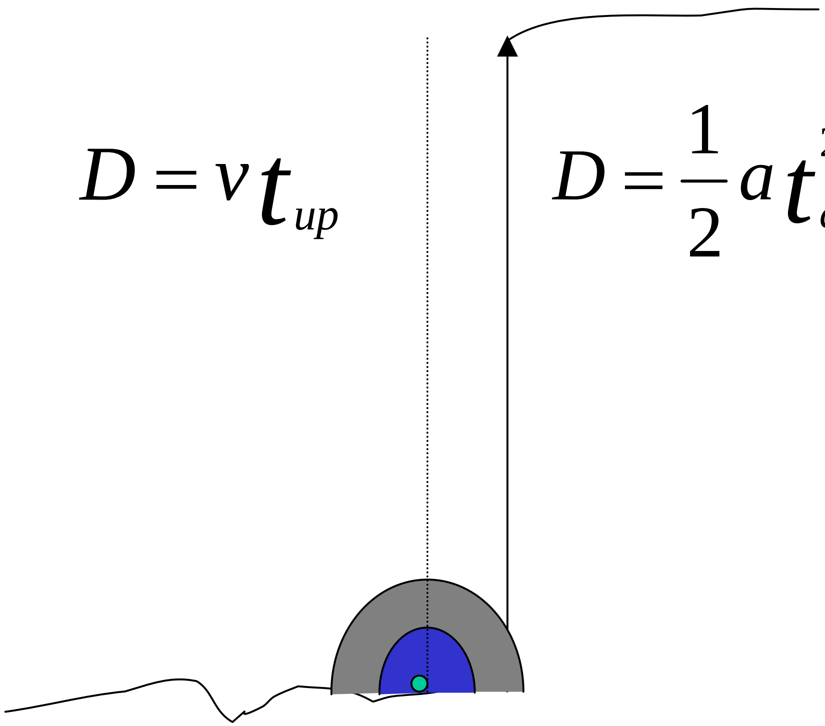
RADAR = **RA**dio **D**etection **A**nd **R**anging

Simple 1D single range example:

Suppose we want to determine how tall a cliff is. We could drop an object from the top. The longer it takes to hear the echo, the taller the cliff. Watermelons or rocks make excellent objects.

Since we know the acceleration of gravity, and the speed of sound, we could estimate the height by timing how long it takes to hear the echo/splat.

Rock and Stopwatch Radar



$$a = 9.8 \frac{m}{s^2}$$

$$D = v\,t_{up}$$

$$D = \frac{1}{2} a\, t_{down}^2$$

$$v = 331.45 \frac{m}{s}$$

$$Time = t_{up} + t_{down}$$

D = Cliff Height

http://www.measure.demon.co.uk/Acoustics_Software/speed.html

Time Measures Distance

$$v(Time - t_{down}) = \frac{1}{2} a t_{down}^2$$

$$\frac{1}{2} a t_{down}^2 + v t_{down} - vTime = 0$$

$$t_{down} = \frac{-v + \sqrt{v^2 + 2avTime}}{a} > 0$$

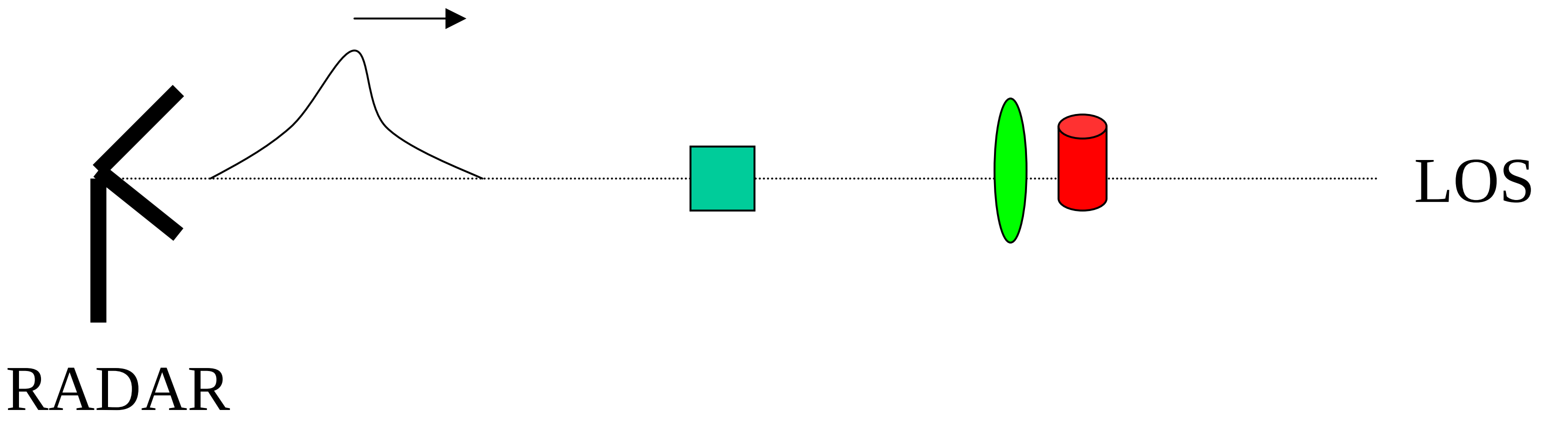
$$D(Time) = \frac{\left(-v + \sqrt{v^2 + 2avTime}\right)^2}{2a}$$

Limitations

- Our example estimates the distance to one object.
- Our accuracy is limited by how quick we can start and stop our timer. (Sampling rate).
- For taller cliffs, it will be harder to hear the echo/splat. Therefore we need bigger rocks/watermelons to generate louder echoes. (Power)

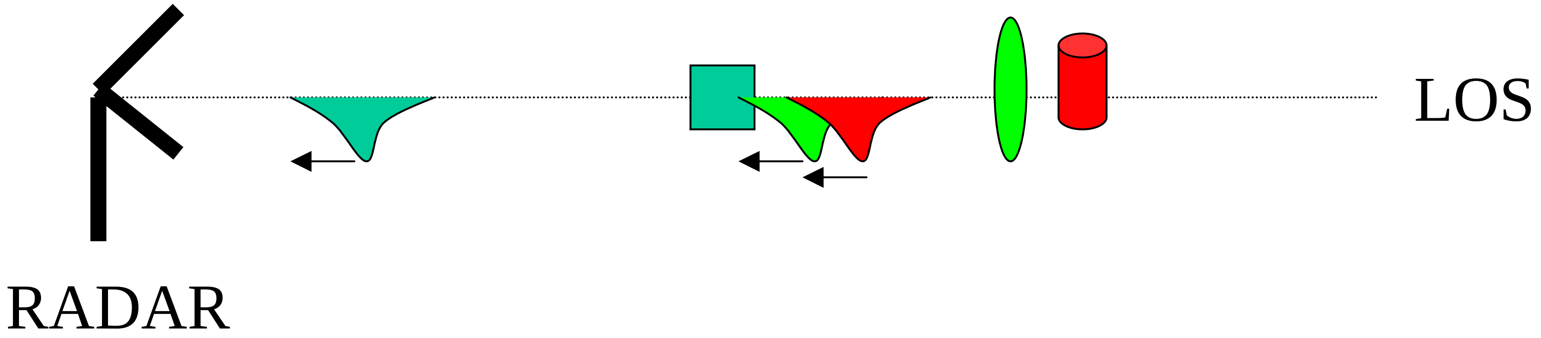
1D RADAR Improvements

- Send a electromagnetic packet of energy toward objects and detect reflections.
  LOS = Line Of Sight



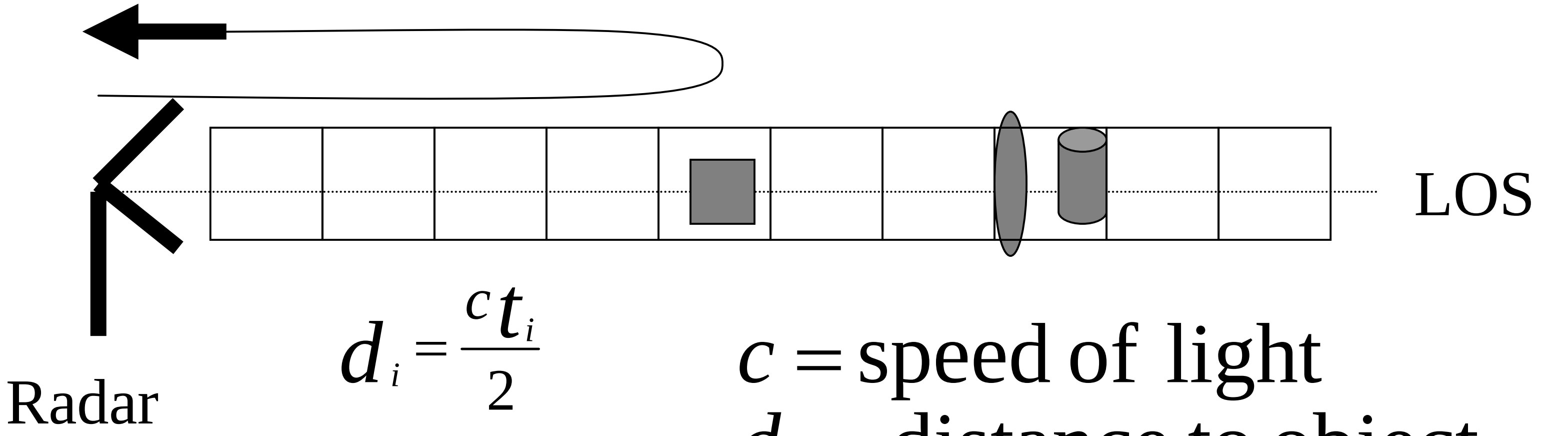
Bandwidth

- A small pulse width allows detection of targets spaced close together. Conflict: small pulse widths require large bandwidths.
- By design, every radar chooses how much resolution (bandwidth) is affordable.



Sampling Rate

- Radars sample return signals at constant intervals, which correspond to time delays, and thus ranges. These discrete ranges are called range bins.

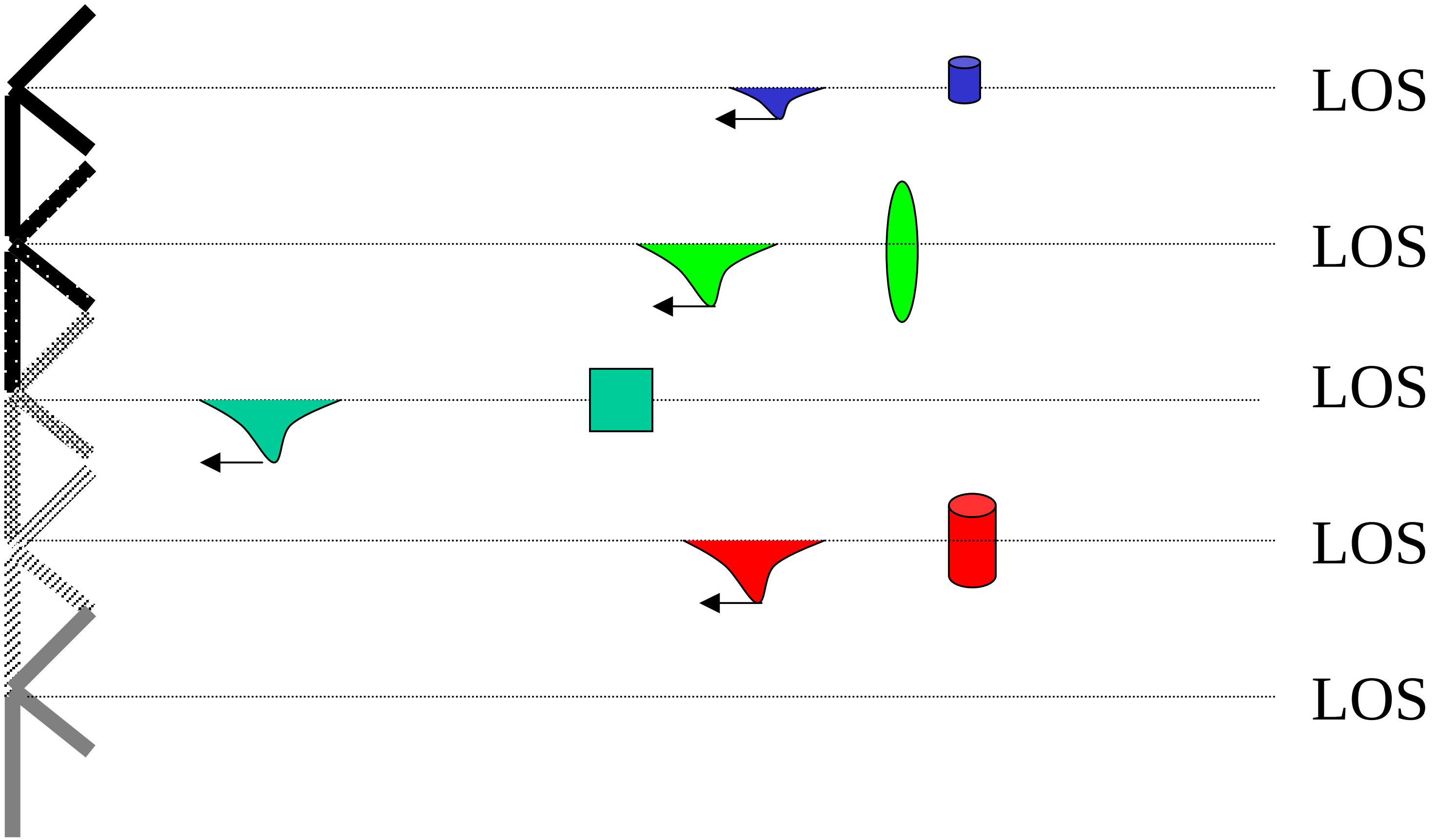


$$d_i = \frac{c t_i}{2}$$

$$c = \text{speed of light}$$
$$d_i = \text{distance to object}_\text{i}$$
$$t_i = \text{roundtrip time to object}_\text{i}$$

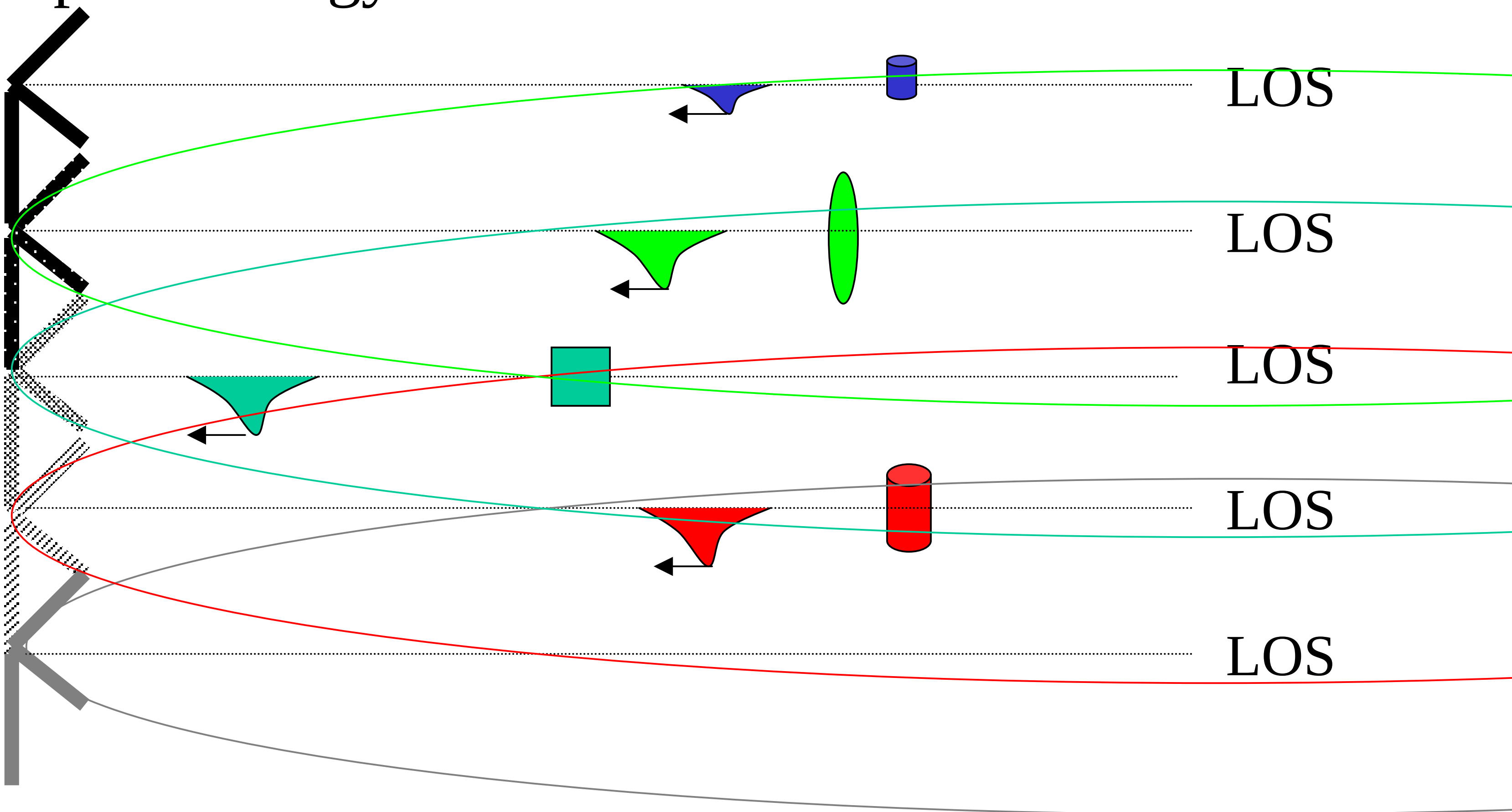
Two Dimensional Radar

- Use the ideal one dimensional radar but move its LOS in cross range for each sample taken.



Antenna Beam Width

- Real antennas do not have pencil width beam patterns. Antennas with larger beam widths capture energy from several LOS.

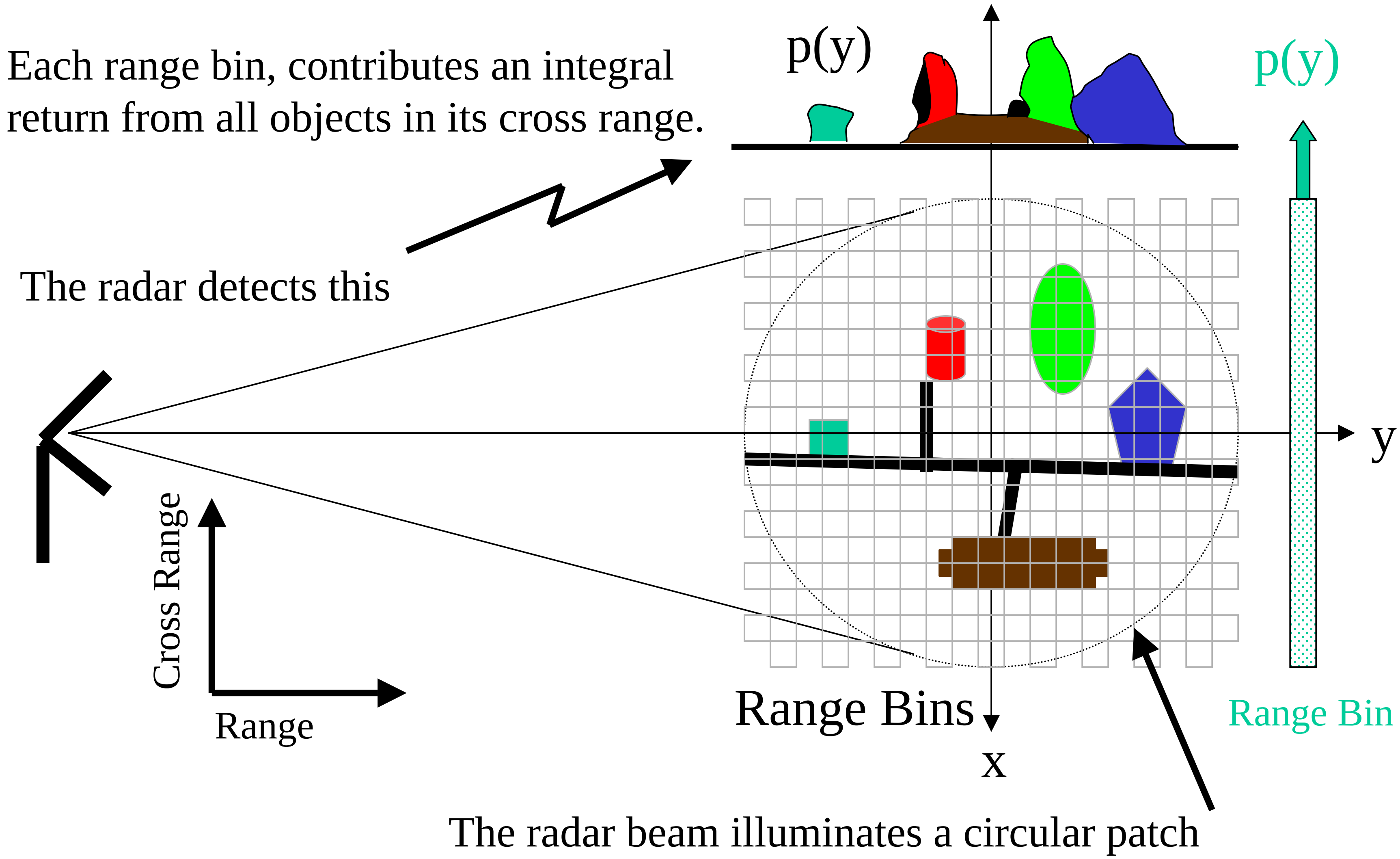


Giant Antennas

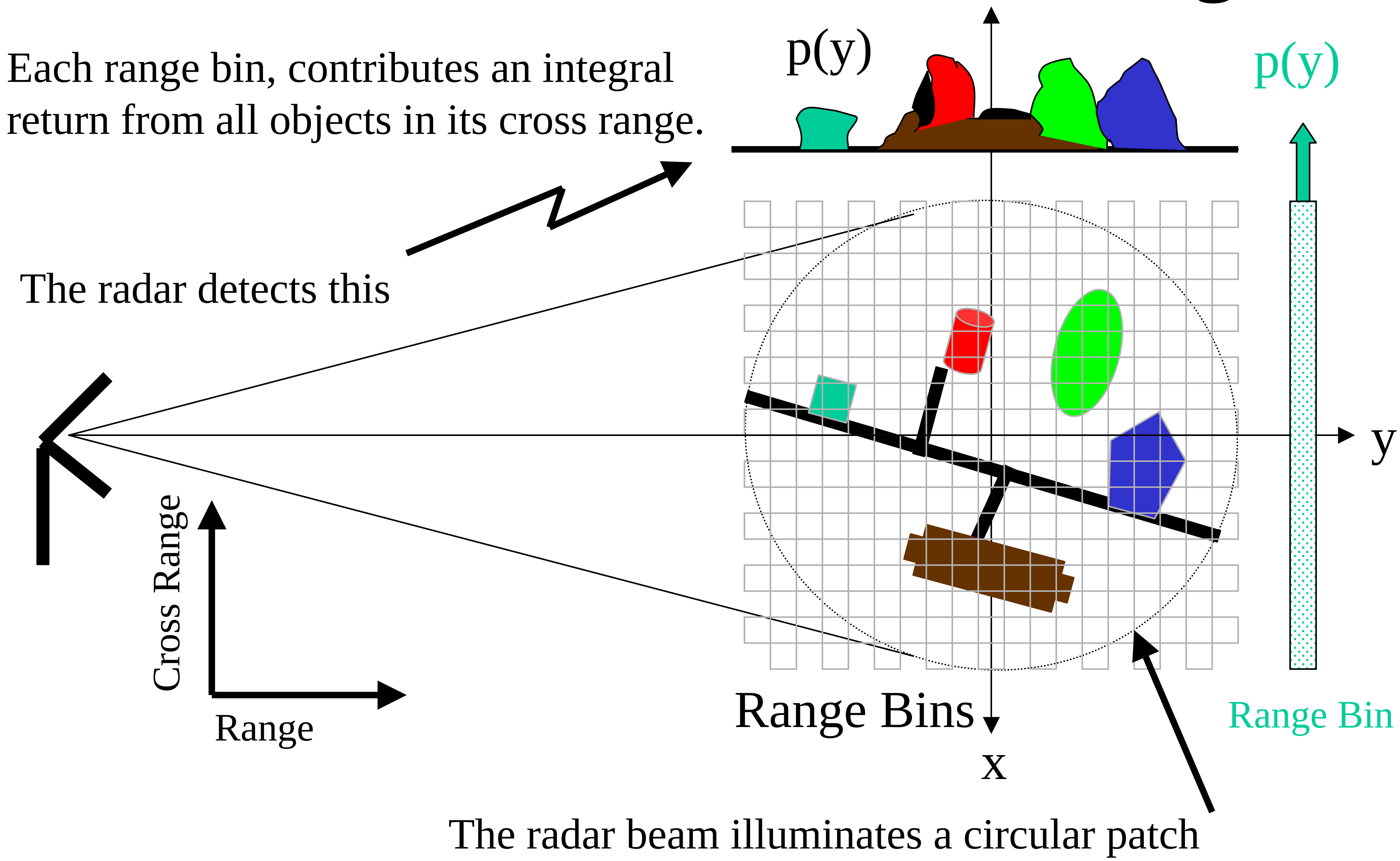
An antenna's apeture width (D), and operating wavelength (λ), are related to the angular beam width (β radians) by approximately $\beta = \dfrac{\lambda}{D}$. At a range of 50km, operating frequency of 10 Ghz, and desired resolution of 0.5 meters

$$D = \frac{0.03 \times 50000}{0.5} = 3000\text{meters}$$

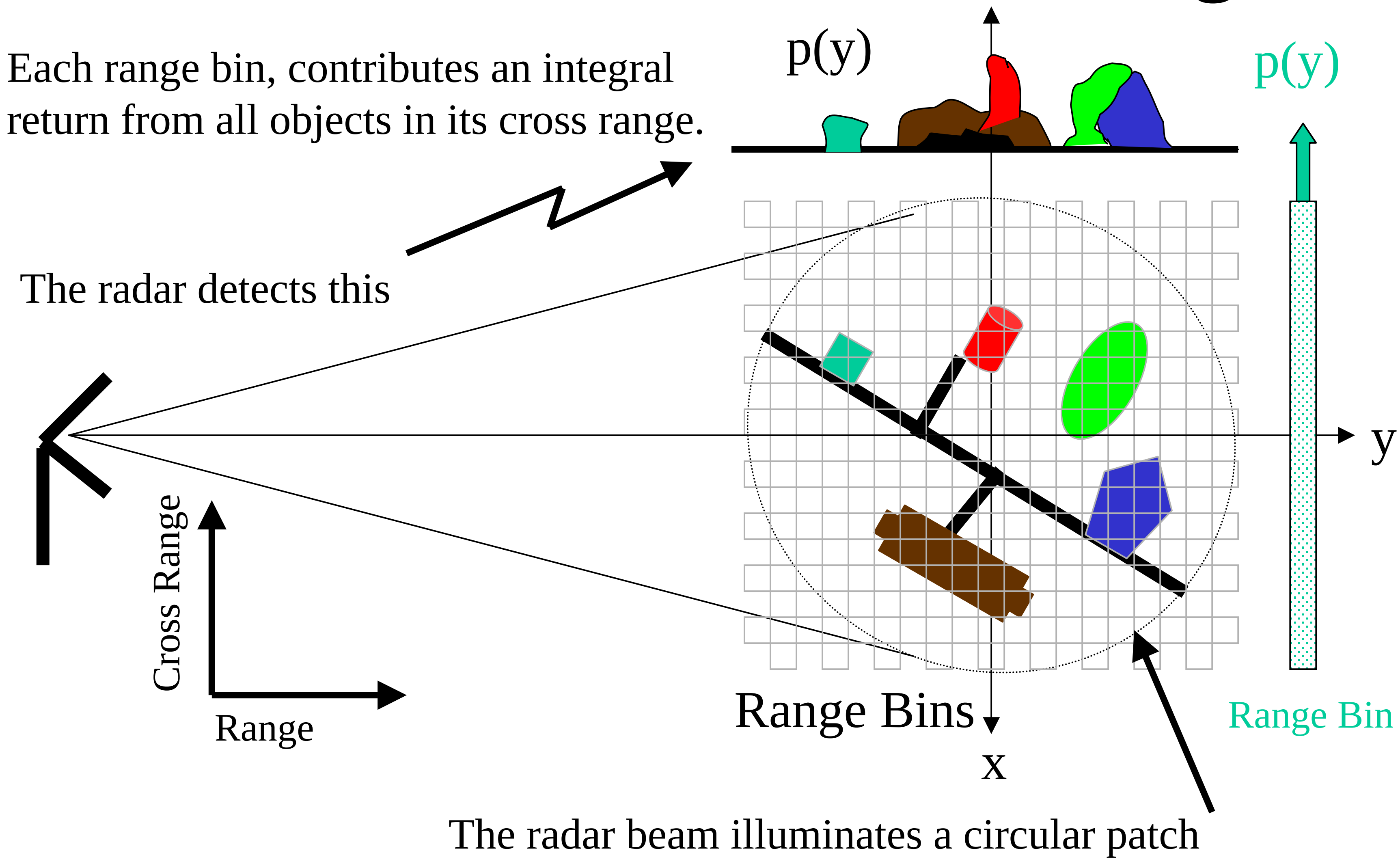
Broad Beam Antennas



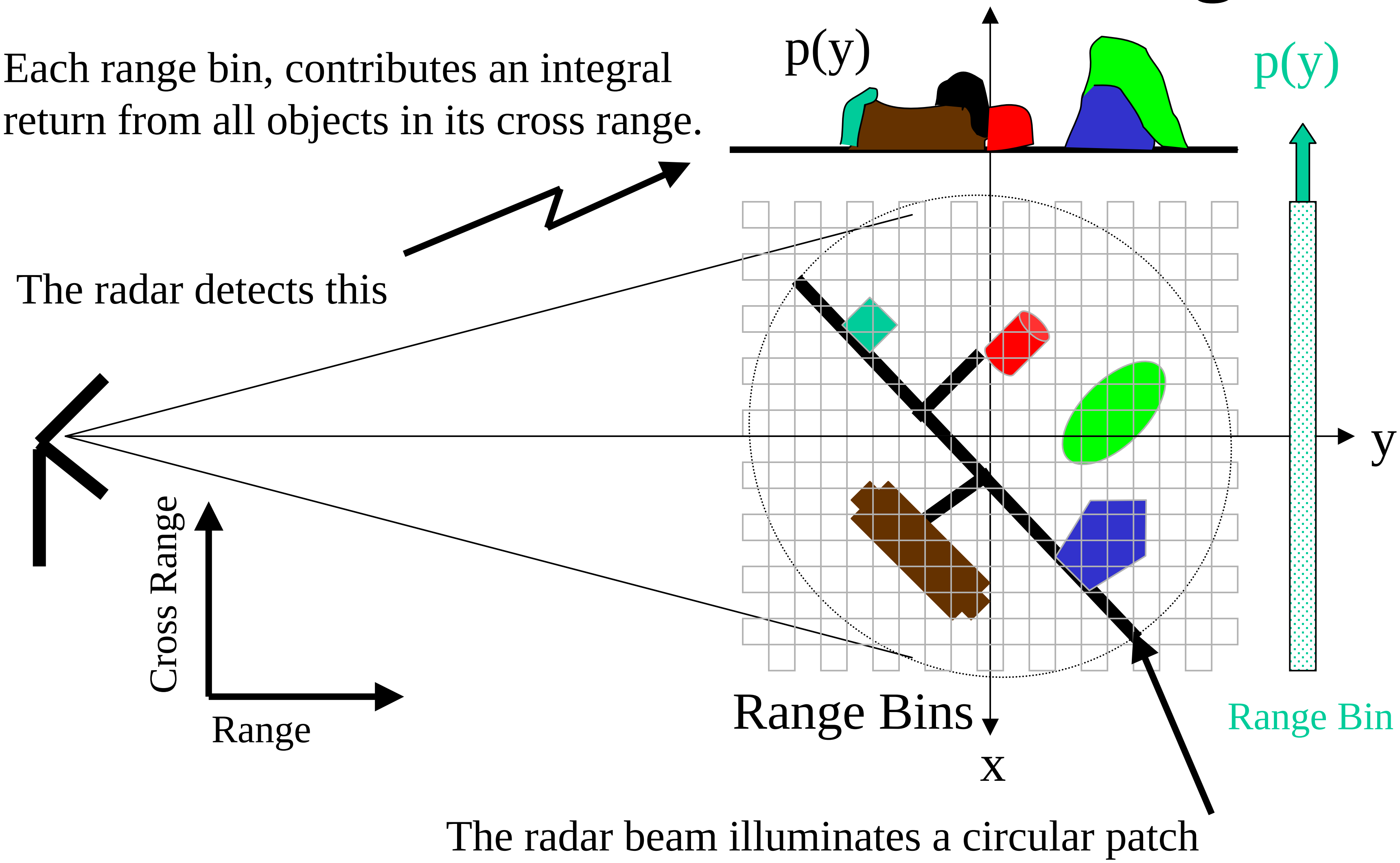
Broad Beam Antennas 15 deg



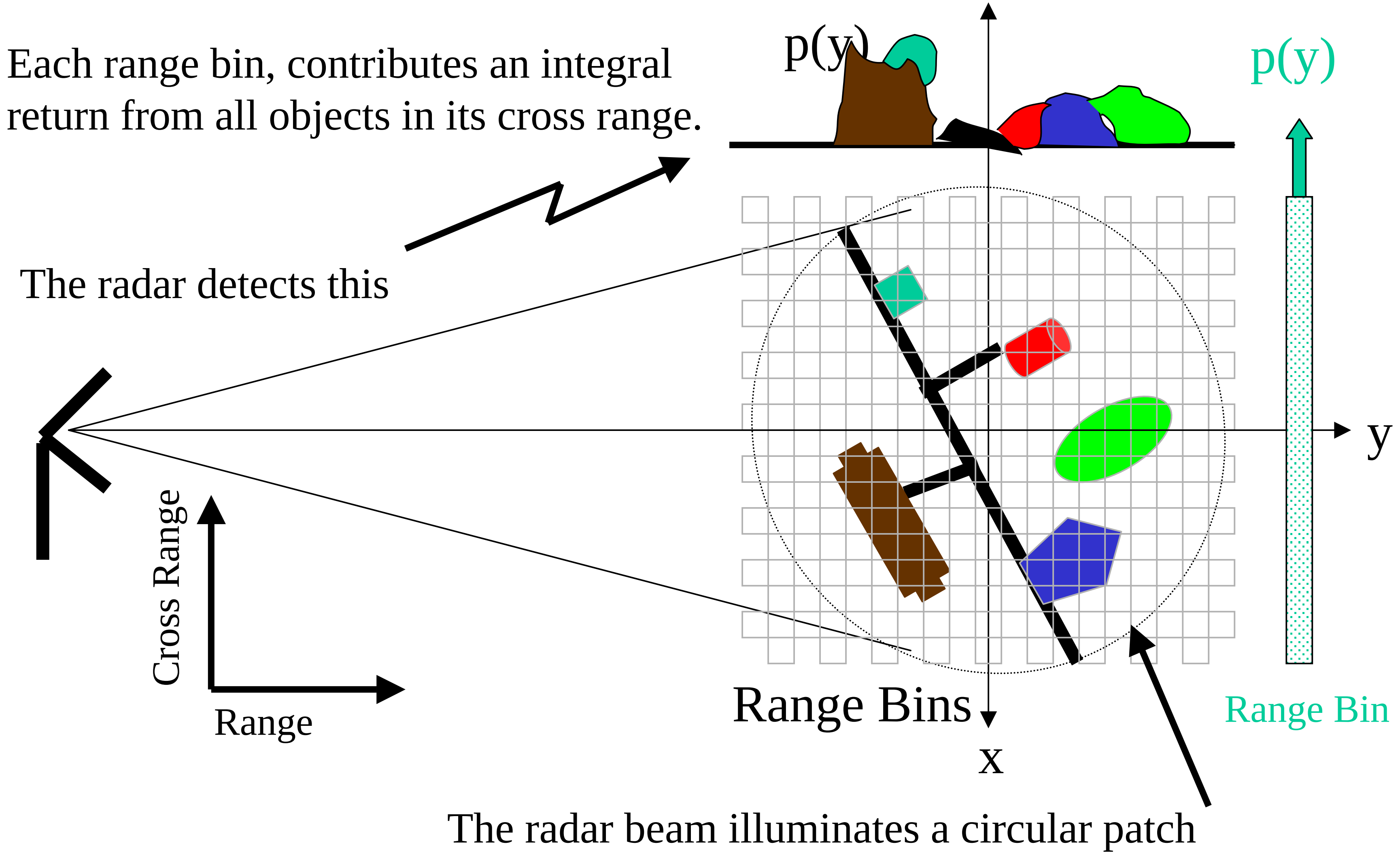
Broad Beam Antennas 30 deg



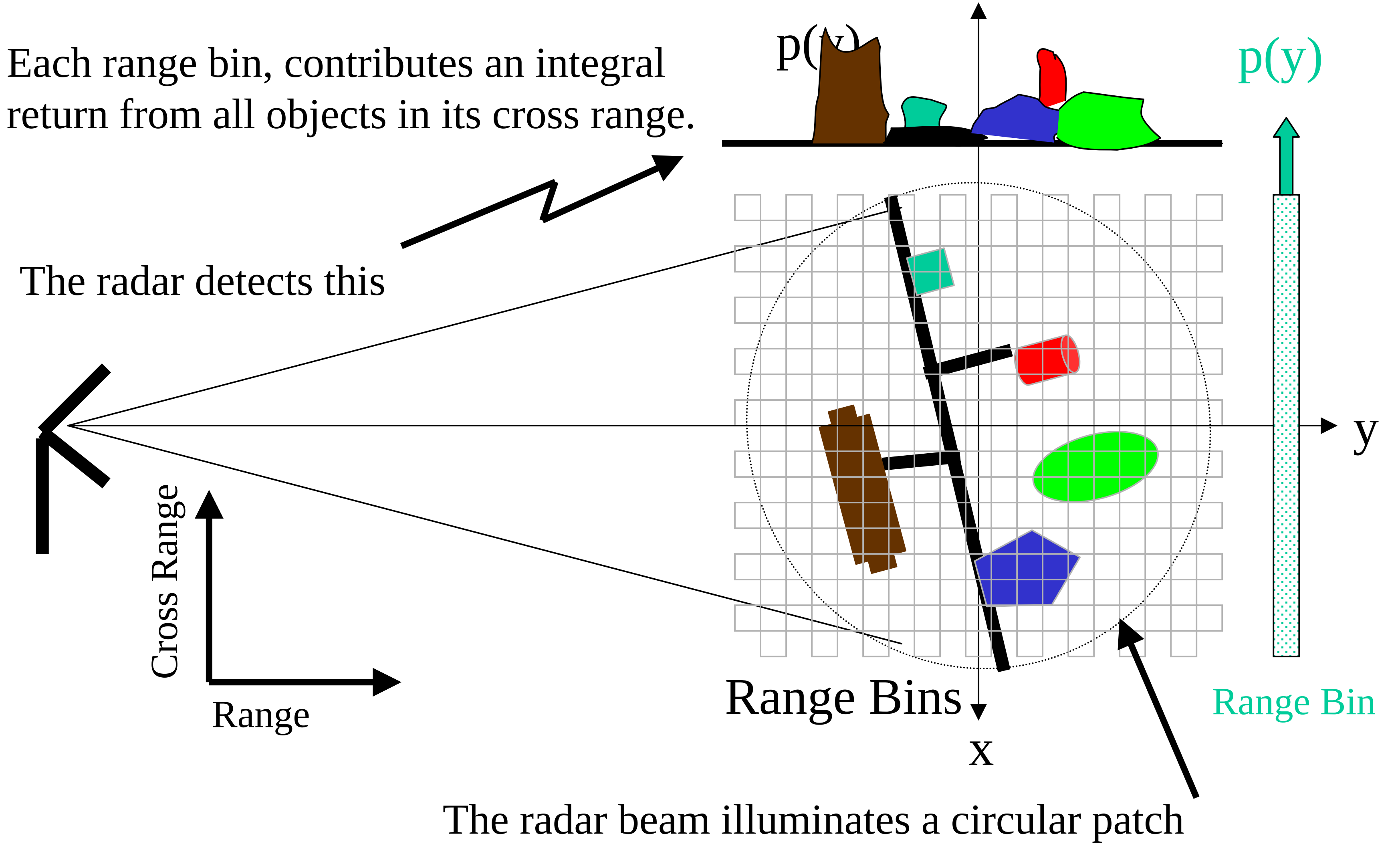
Broad Beam Antennas 45 deg



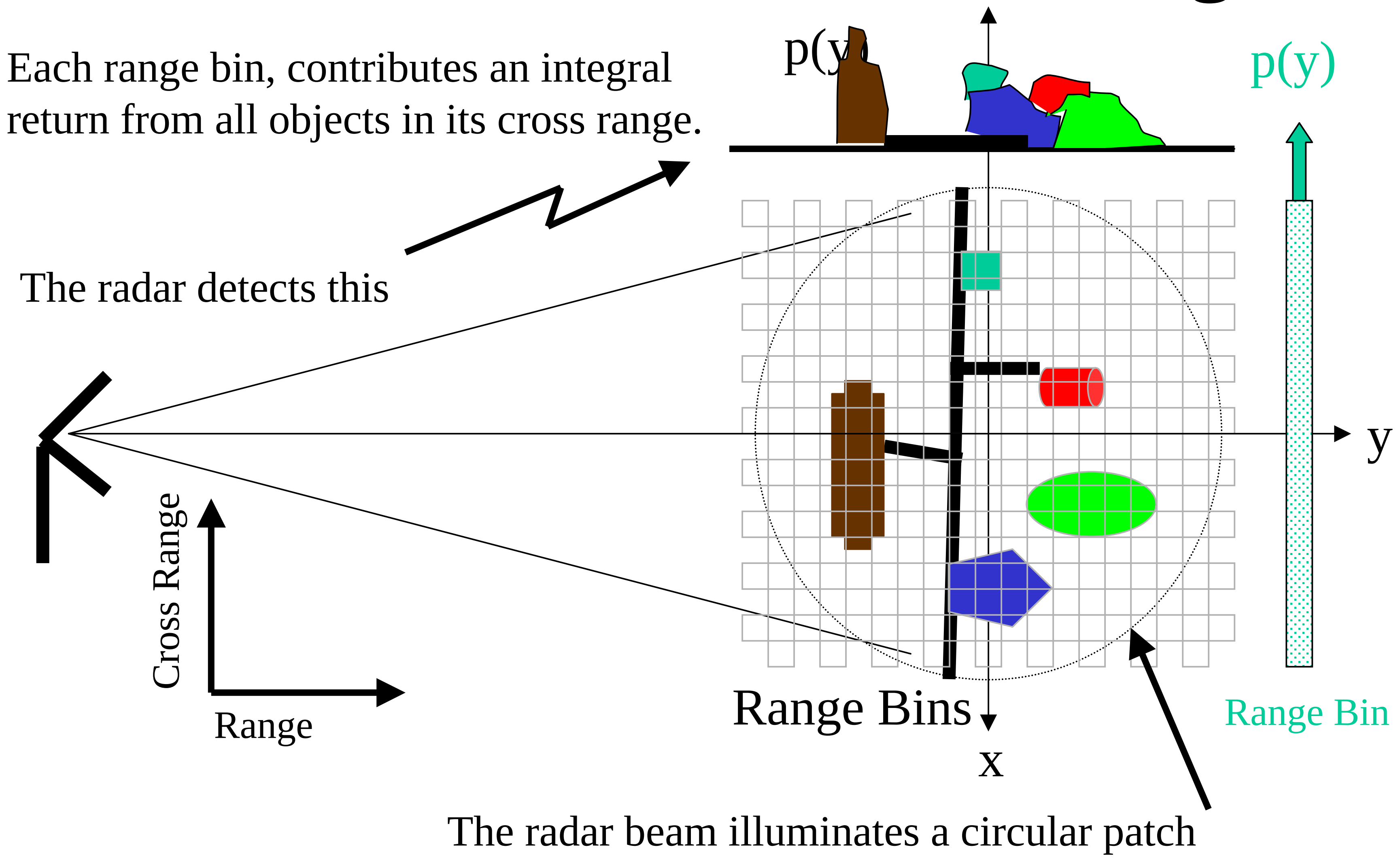
Broad Beam Antennas 60 deg



Broad Beam Antennas 75 deg

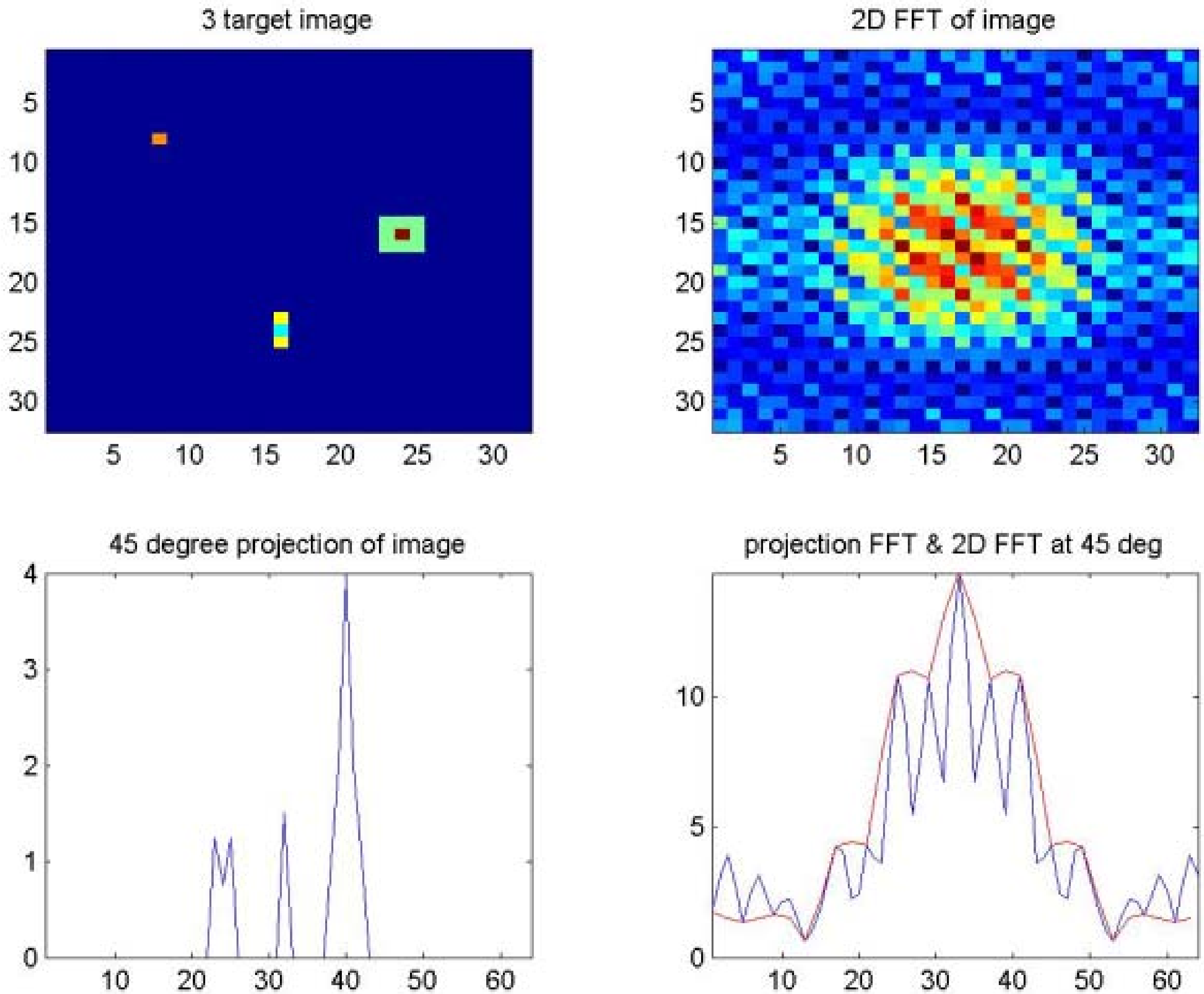


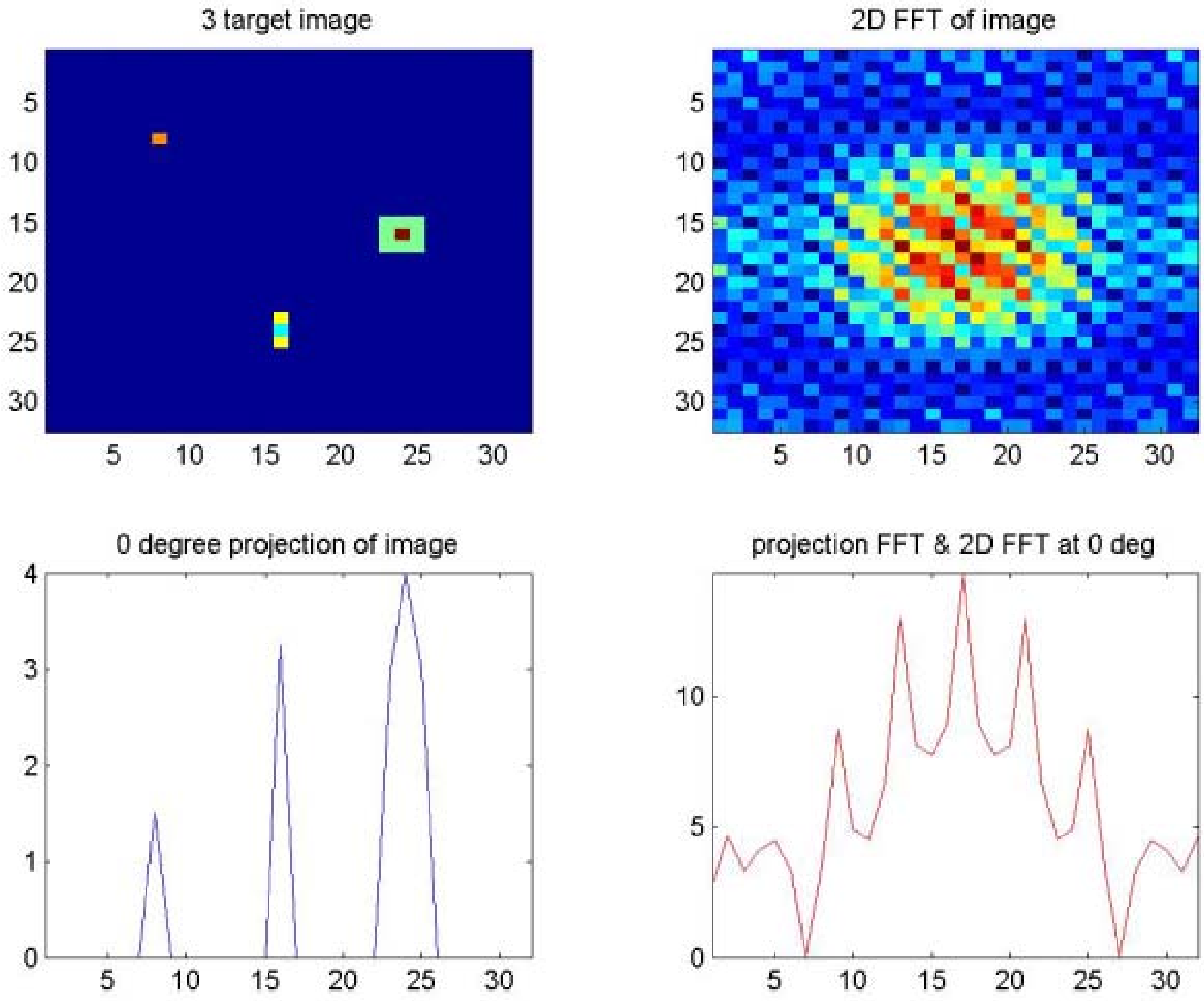
Broad Beam Antennas 90 deg

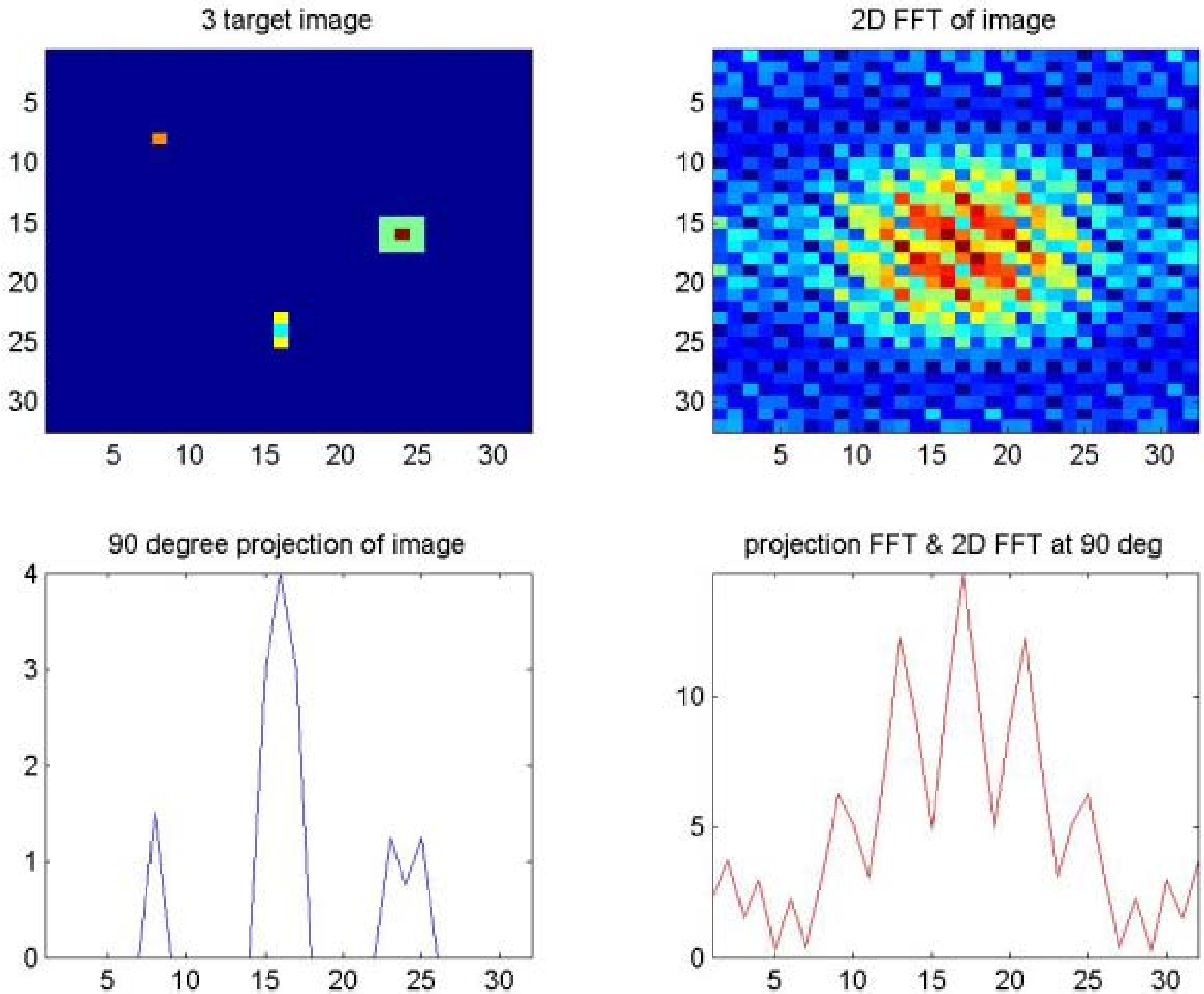


Projection Slice Theorem

- The 1D Fourier transform of the projection of an image along an angle θ is equal to the 2D Fourier transform of the same image evaluated along a line in the Fourier domain at the same angle θ.

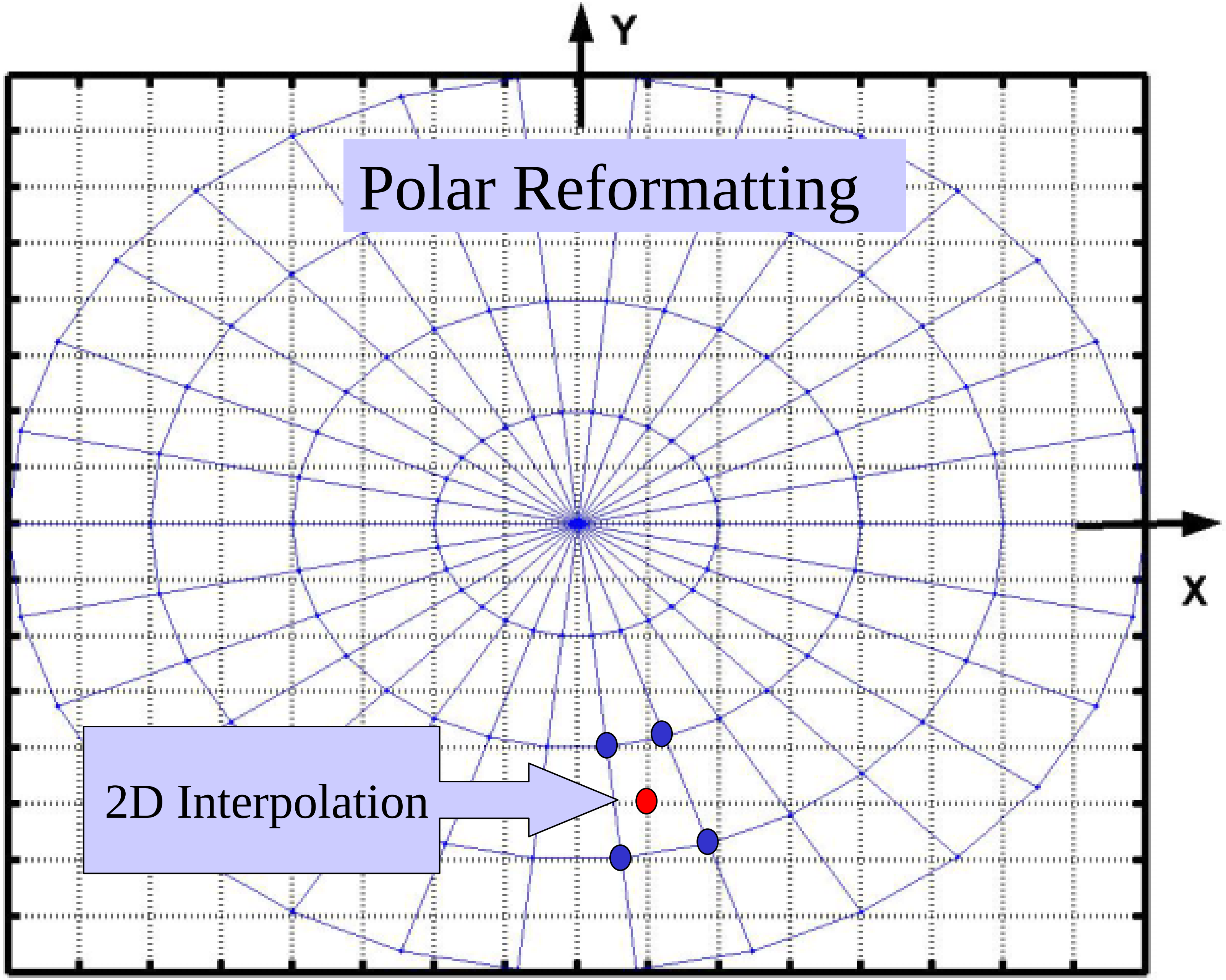

3 target image
2D FFT of image
45 degree projection of image
projection FFT & 2D FFT at 45 deg


3 target image
2D FFT of image
0 degree projection of image
projection FFT & 2D FFT at 0 deg


3 target image
2D FFT of image
90 degree projection of image
projection FFT & 2D FFT at 90 deg

Polar Reformatting

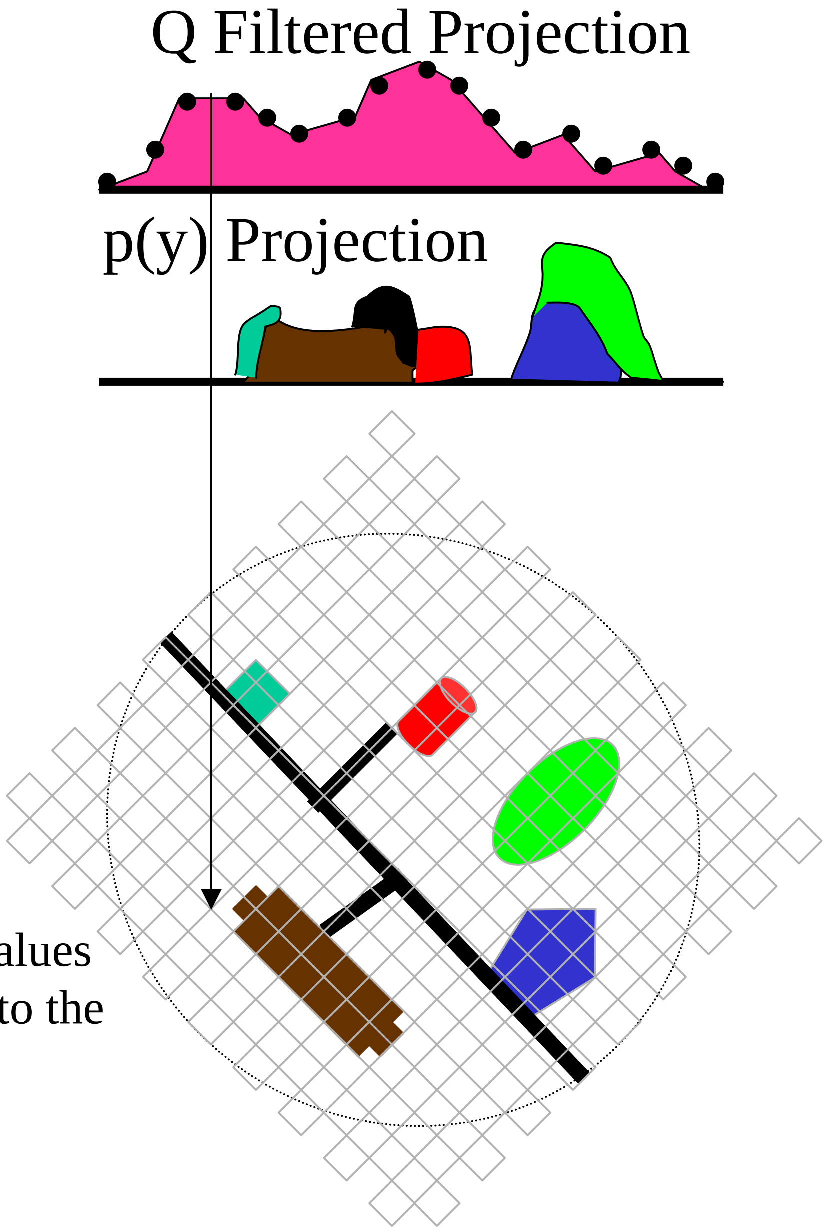
- The radar measures projections $p(\theta)$ at many angles.
- Projections are transformed P=fft(p) and combined to approximate the 2D FFT (G) of the image.
- An inverse FFT g(x,y)=IFFT(G) can be applied, and the image estimated.


Y
Polar Reformatting
X
2D Interpolation

Convolution/Back Projection

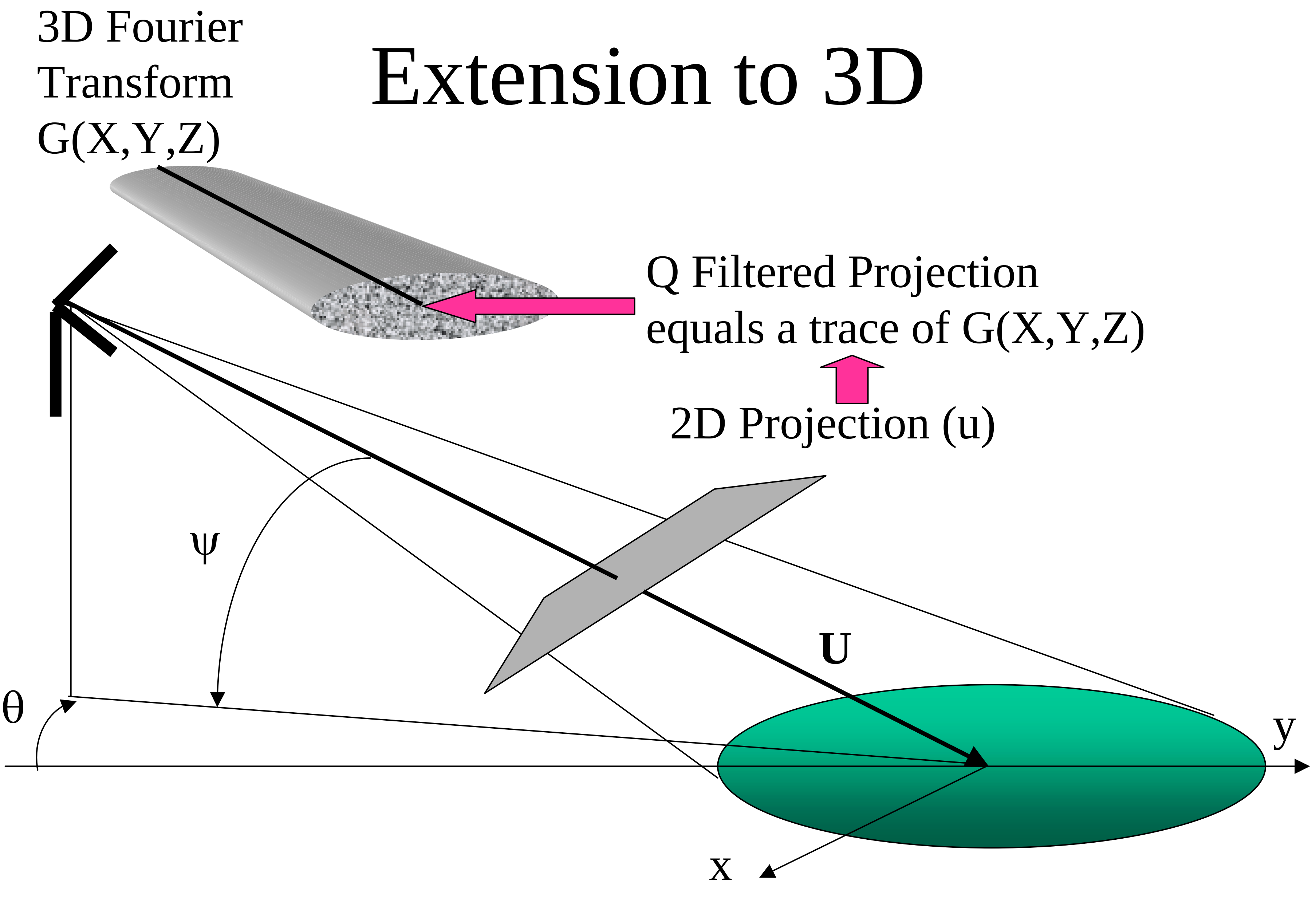
- Rewrite the inverse Fourier transform in polar coordinates $g(\rho\cos\phi, \rho\sin\phi)$.
- Identify the filtering kernel $h(\rho)$.
- Define Q as the projection function $p(\theta)$ convolved with the filtering kernel $h(\rho)$.
- Each image location $g(x,y)$ is then found as the sum of the filtered projection functions back projected.
- Only 1D interpolation required

Convolution/Back Projection

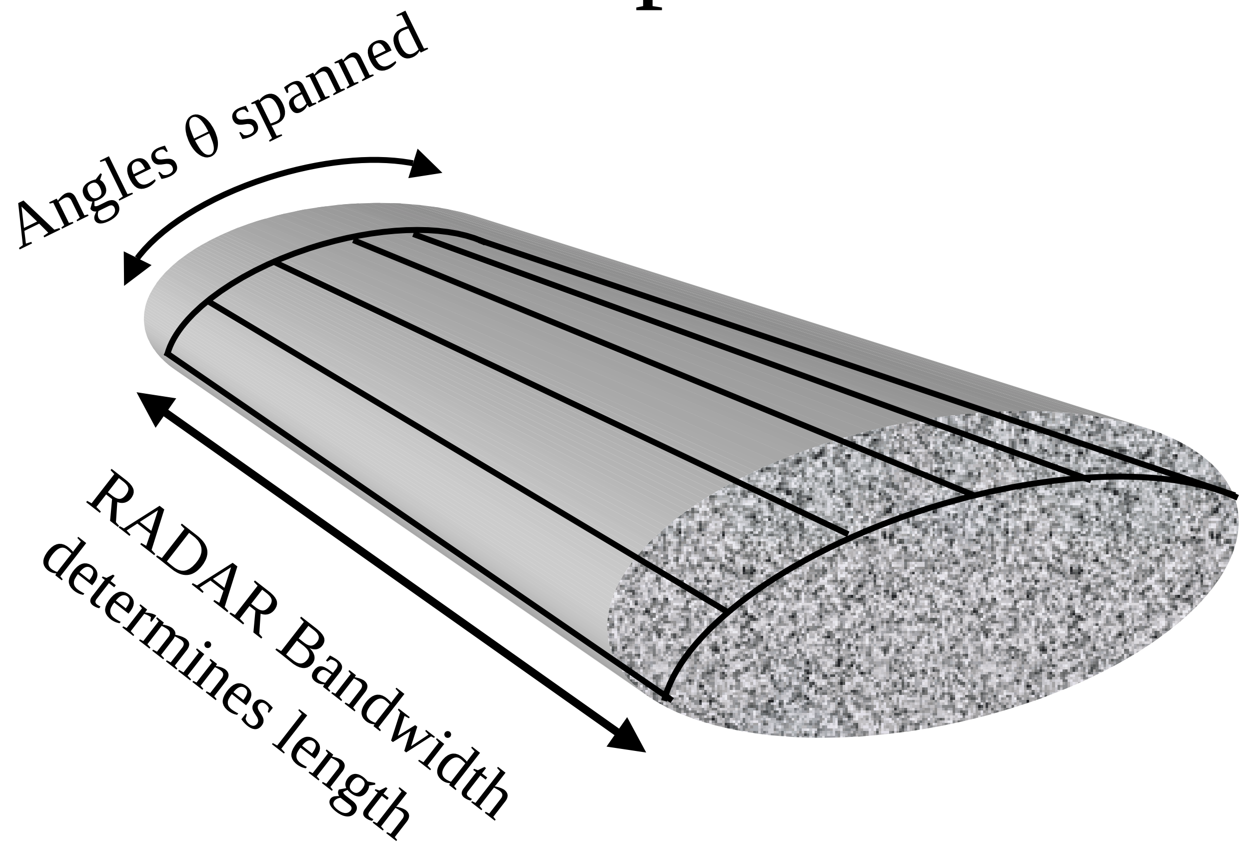


1D Interpolated values back projected onto the image grid

Extension to 3D



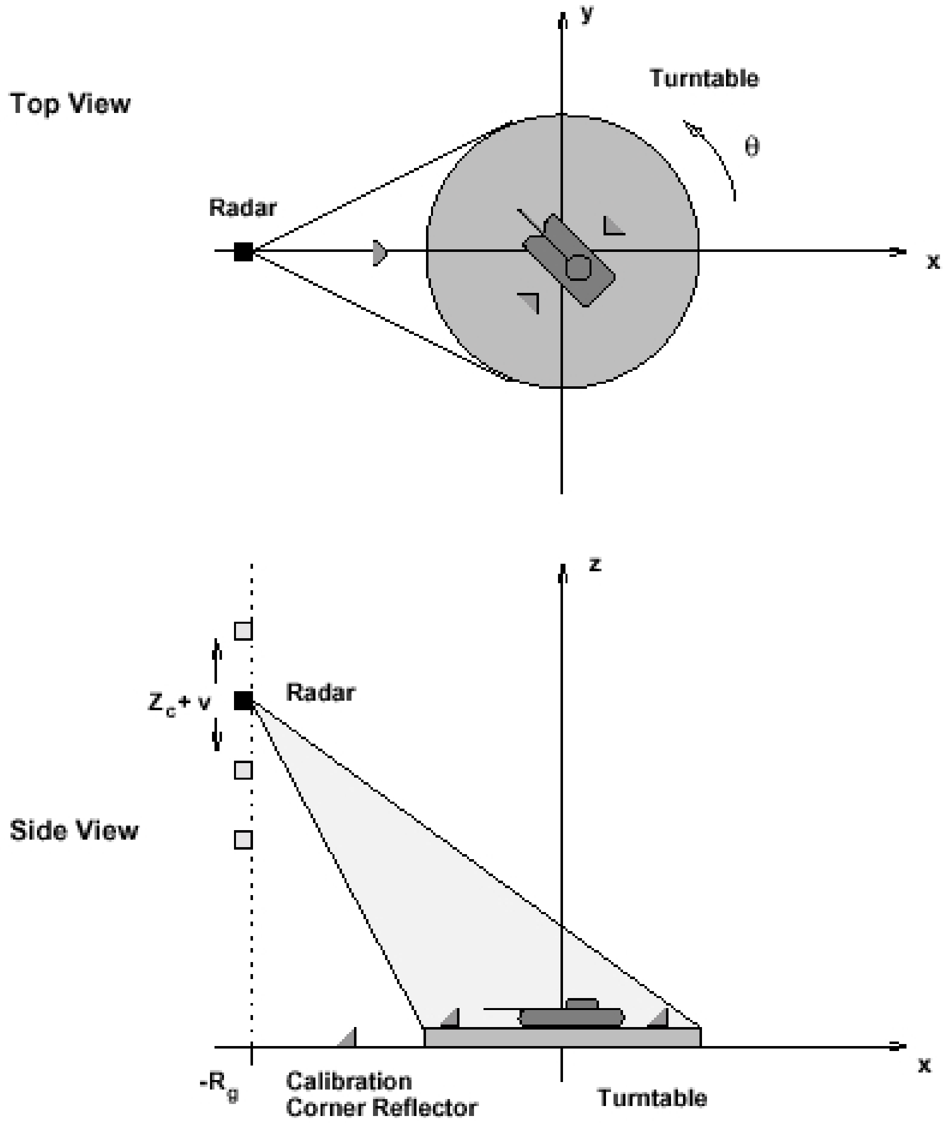
Ribbon Surface of 3D Fourier Space



Possible Errors - Corrected

- Range/location error
- Carrier frequency drift
- Main SAR beam off center
- Interpolation and projection errors
- Aliasing
- Targets moving during measurements

Turn Table Setup



Algorithm

- Convert measured data into MATLAB arrays for a given aspect and aperture.
- Generate calibration data and then calibrate against measured data.
- Correct data for aliasing
- Perform back projection
- Generate a 3D image

Parallel Algorithm

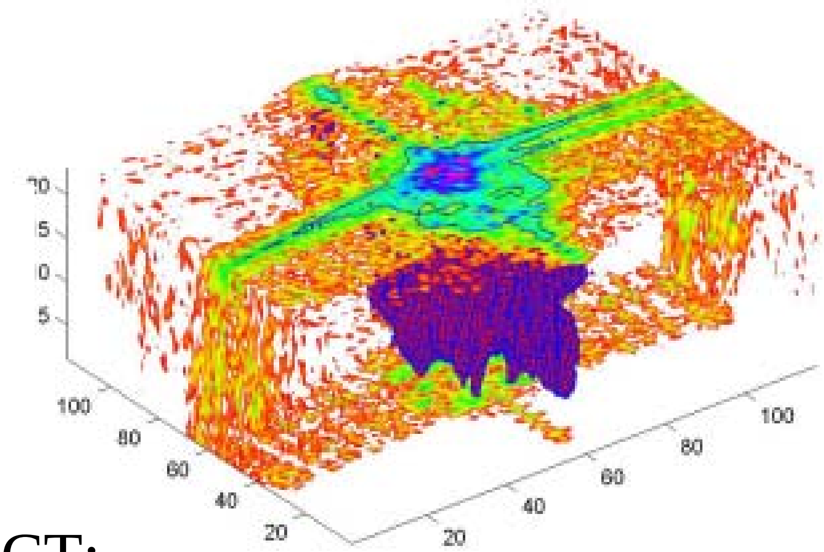
- Divide aspect angles among processors.
- Convert MATLAB code to C and port to UNIX. DOS vs. UNIX names change.
- Wrap C code with MPI routines.
- Port results back to interactive MATLAB for visualization.

3D Synthetic Aperture RADAR (3DSAR)

10 hours processing time to create one image at one angle on a 1GHz NT workstation.

5,000 times speedup on HPC resources. Generates all 360 angles at 1 degree resolution.

41 minutes total time



IMPACT:

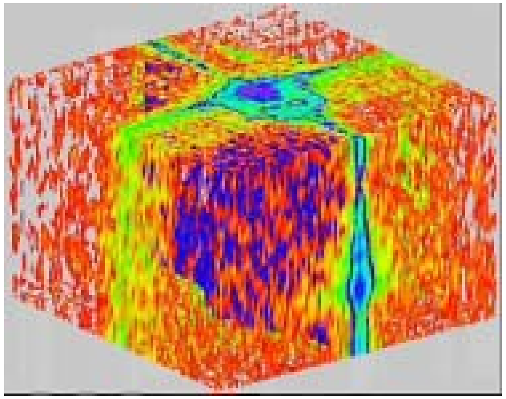
The programs impacted are the high frequency radar ATR programs. High frequency radars have the resolution to support high performance ATR. The specific programs include AFRL's

Time Critical Targeting (TCT) ATR which is looking at transitioning ATR for Recce radars.

Air-to-Ground Radar Imaging (AGRI) program which is looking to transition ATR for strike platforms for both stationary and moving ground targets. The stationary part uses SAR and the moving part uses High Range Resolution (HRR). In both cases, 3D SAR data makes an excellent source of training data.

Image vs. aspect angle movies

- Aliased returns shown every 5 degrees of aspect with a aperture size of 4 degrees.



- Unaliased version